Introduction to Software Testing
Chapter 9.2
Program-based Grammars

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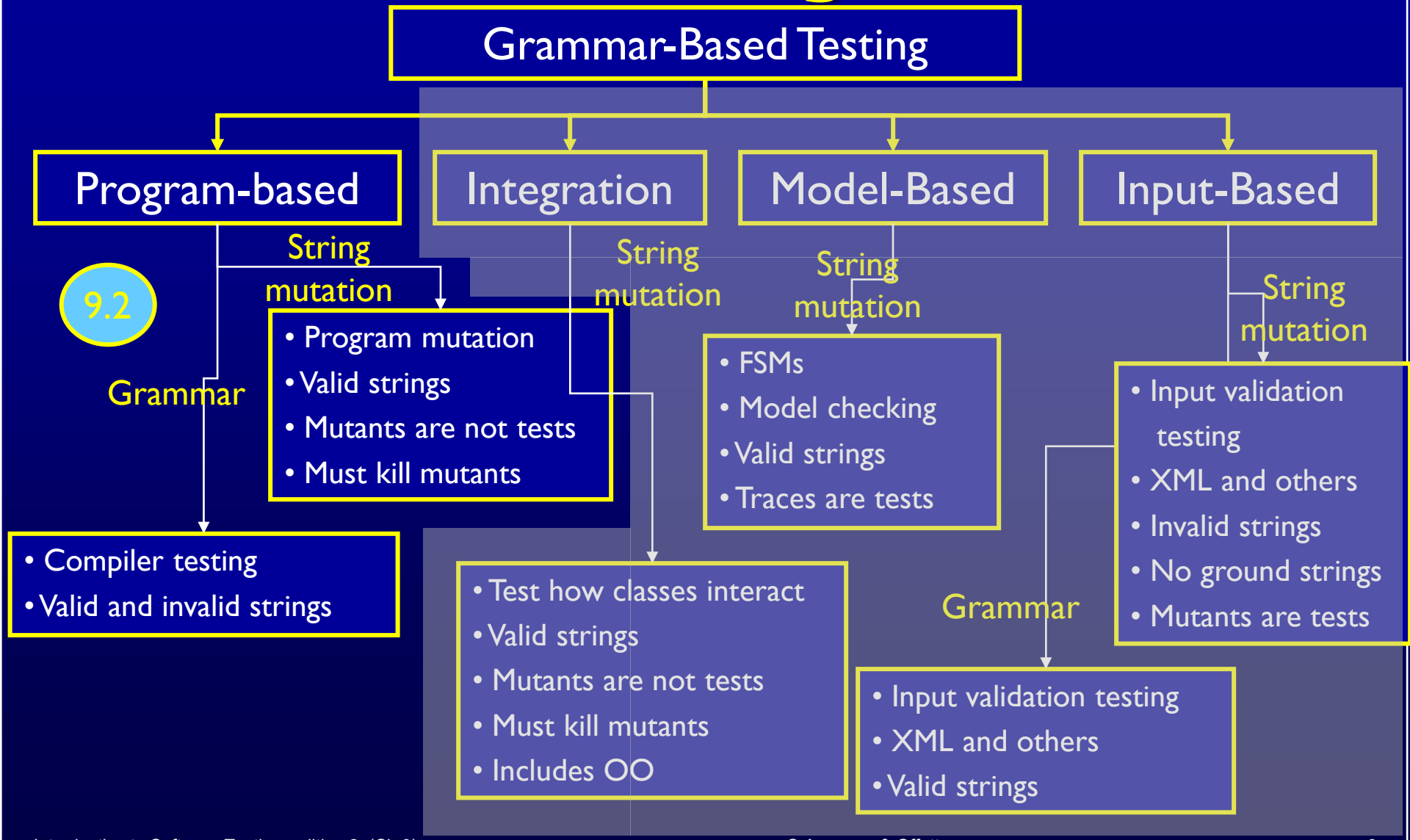
Applying Syntax-based Testing to Programs

- Syntax-based criteria originated with programs and have been used mostly with programs
- BNF criteria are most commonly used to test compilers
- Mutation testing criteria are most commonly used for unit testing and integration testing of classes

Instantiating Grammar-Based Testing



BNF Testing for Compilers (9.2.1)

- Testing compilers is very complicated
  - Millions of correct programs !
  - Compilers must recognize and reject incorrect programs
- BNF criteria can be used to generate programs to test all language features that compilers must process
- This is a very specialized application and not discussed in detail

Program-based Grammars (9.2.2)

- The original and most widely known application of syntax-based testing is to modify programs
- Operators modify a ground string (program under test) to create mutant programs
- Mutant programs must compile correctly (valid strings)
- Mutants are not tests, but used to find tests
- Once mutants are defined, tests must be found to cause mutants to fail when executed
- This is called "killing mutants"

Killing Mutants

Given a mutant $m \in M$ for a ground string program P and a test t, t is said to kill m if and only if the output of t on P is different from the output of t on m.

- If mutation operators are designed well, the resulting tests will be very powerful
- Different operators must be defined for different programming languages and different goals
- Testers can keep adding tests until all mutants have been killed
  - *Dead mutant* : A test case has killed it
  - *Stillborn mutant* : Syntactically illegal
  - *Trivial mutant* : Almost every test can kill it
  - *Equivalent mutant* : No test can kill it (same behavior as original)

Program-based Grammars

Original Method

```
int Min (int A, int B)
{
        int minVal;
        minVal = A;
        if (B < A)
        {
            minVal = B;
         }
         return (minVal);
} // end Min
```

6 mutants

Each represents a separate program

With Embedded Mutants

```
int Min (int A, int B)
{
        int minVal;
        minVal = A;
Δ 1     minVal = B;
        if (B < A)
Δ 2     if (B > A)
Δ 3     if (B < minVal)
        {
                minVal = B;
Δ 4             Bomb ();
Δ 5             minVal = A;
Δ 6             minVal = failOnZero (B);
        }
        return (minVal);
} // end Min
```

Replace one variable with another

Replaces operator

Immediate runtime failure … if reached

Immediate runtime failure if B==0, else does nothing

Syntax-Based Coverage Criteria

Mutation Coverage (MC) : For each $m \in M$, TR contains exactly one requirement, to kill m.

- The RIPR model from chapter 2:
  - *Reachability* : The test causes the faulty statement to be reached (in mutation – the mutated statement)
  - *Infection* : The test causes the faulty statement to result in an incorrect state
  - *Propagation* : The incorrect state propagates to incorrect output
  - *Revealability* : The tester must observe part of the incorrect output
- The RIPR model leads to two variants of mutation coverage …

Syntax-Based Coverage Criteria

1) Strongly Killing Mutants:

Given a mutant $m \in M$ for a program P and a test t, t is said to *strongly kill* m if and only if the output of t on P is different from the output of t on m

2) Weakly Killing Mutants:

Given a mutant $m \in M$ that modifies a location l in a program P, and a test t, t is said to *weakly kill* m if and only if the state of the execution of P on t is different from the state of the execution of m on t immediately after l

- Weakly killing satisfies reachability and infection, but not propagation

Weak Mutation

Weak Mutation Coverage (WMC) : For each $m \in M$, TR contains exactly one requirement, to weakly kill m.

- "Weak mutation" is so named because it is easier to kill mutants under this assumption
- Weak mutation also requires less analysis
- A few mutants can be killed under weak mutation but not under strong mutation (no propagation)
- Studies have found that test sets that weakly kill all mutants also strongly kill most mutants

Weak Mutation Example

- Mutant 1 in the Min( ) example is:

```
     minVal = A;
Δ 1  minVal = B;
     if (B < A)
         minVal = B;
```

- The complete test specification to kill mutant 1:

- Reachability : *true* // Always get to that statement
- Infection : $A \neq B$
- Propagation: $(B < A) = false$ // Skip the next assignment
- Full Test Specification : *true* $\wedge$ $(A \neq B) \wedge ((B < A) = false)$
  $\equiv (A \neq B) \wedge (B \geq A)$
  $\equiv (B > A)$

- Weakly kill mutant 1, but not strongly? A = 5, B = 3

Equivalent Mutation Example

- Mutant 3 in the Min() example is equivalent:

```
      minVal = A;
      if (B < A)
Δ 3   if (B < minVal)
```

- The infection condition is "(B < A) != (B < minVal)"

- However, the previous statement was "minVal = A"
  - Substituting, we get: "(B < A) != (B < A)"
  - This is a logical contradiction !

- Thus no input can kill this mutant

Strong Versus Weak Mutation

```
1     boolean isEven (int X)
2     {
3         if (X < 0)
4             X = 0 - X;
Δ 4           X = 0;
5         if (double) (X/2) == ((double) X) / 2.0
6             return (true);
7         else
8             return (false);
9     }
```

Reachability : X < 0

Infection : X != 0

(X = -6) will kill mutant 4 under weak mutation

Propagation :

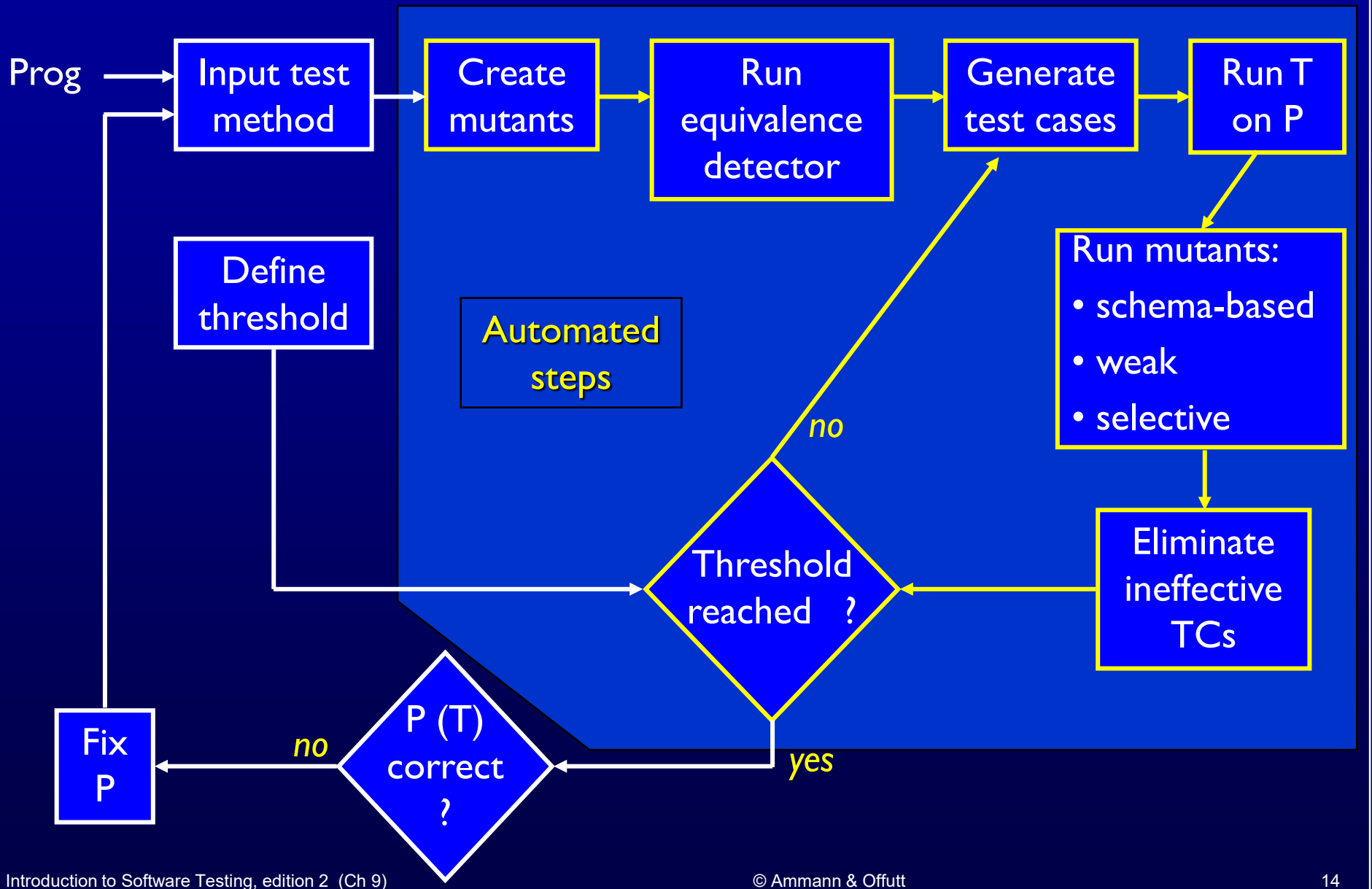
((double) ((0-X)/2) == ((double) 0-X) / 2.0)

!= ((double) (0/2) == ((double) 0) / 2.0)

That is, X is not even …

Thus (X = -6) does *not* kill the mutant under strong mutation

Testing Programs with Mutation



Why Mutation Works

Fundamental Premise of Mutation Testing

If the software contains a fault, there will usually be a set of mutants that can only be killed by a test case that also detects that fault

- This is not an absolute !
- The mutants guide the tester to an effective set of tests
- A very challenging problem :
  - Find a fault and a set of mutation-adequate tests that do not find the fault
- Of course, this depends on the mutation operators …

Designing Mutation Operators

- At the method level, mutation operators for different programming languages are similar
- Mutation operators do one of two things :
  - Mimic typical programmer mistakes (incorrect variable name)
  - Encourage common test heuristics (cause expressions to be 0)
- Researchers design lots of operators, then experimentally *select* the most useful

Effective Mutation Operators

If tests that are created specifically to kill mutants created by a collection of mutation operators *O* = {*o1*, *o2*, …} also kill mutants created by all remaining mutation operators with very high probability, then *O* defines an *effective* set of mutation operators

Mutation Operators for Java

1. ABS — Absolute Value Insertion
2. AOR — Arithmetic Operator Replacement
3. ROR — Relational Operator Replacement
4. COR — Conditional Operator Replacement
5. SOR — Shift Operator Replacement
6. LOR — Logical Operator Replacement
7. ASR — Assignment Operator Replacement
8. UOI — Unary Operator Insertion
9. UOD — Unary Operator Deletion
10. SVR — Scalar Variable Replacement
11. BSR — Bomb Statement Replacement

Full definitions …

Mutation Operators for Java

1. ABS — Absolute Value Insertion:

Each arithmetic expression (and subexpression) is modified by the functions *abs()*, *negAbs()*, and *failOnZero()*.

Examples:

```
      a = m * (o + p);
Δ1    a = abs (m * (o + p));
Δ2    a = m * abs ((o + p));
Δ3    a = failOnZero (m * (o + p));
```

2. AOR — Arithmetic Operator Replacement:

Each occurrence of one of the arithmetic operators +, −, *, /, and % is replaced by each of the other operators. In addition, each is replaced by the special mutation operators *leftOp*, and *rightOp*.

Examples:

```
      a = m * (o + p);
Δ1    a = m + (o + p);
Δ2    a = m * (o * p);
Δ3    a = m leftOp (o + p);
```

Mutation Operators for Java (2)

3. ROR — Relational Operator Replacement:

Each occurrence of one of the relational operators (<, ≤, >, ≥, =, ≠) is replaced by each of the other operators and by *falseOp* and *trueOp*.

Examples:

```
      if (X <= Y)
Δ1    if (X > Y)
Δ2    if (X < Y)
Δ3    if (X falseOp Y)  // always returns false
```

4. COR — Conditional Operator Replacement:

Each occurrence of one of the logical operators (and - &&, or - || , and with no conditional evaluation - &, or with no conditional evaluation - |, not equivalent - ^) is replaced by each of the other operators; in addition, each is replaced by *falseOp*, *trueOp*, *leftOp*, and *rightOp*.

Examples:

```
      if (X <= Y && a > 0)
Δ1    if (X <= Y || a > 0)
Δ2    if (X <= Y leftOp a > 0) // returns result of left clause
```

Mutation Operators for Java (4)

5. SOR — Shift Operator Replacement:

Each occurrence of one of the shift operators <<, >>, and >>> is replaced by each of the other operators. In addition, each is replaced by the special mutation operator *leftOp*.

Examples:

```
      byte b = (byte) 16;
      b = b >> 2;
Δ1    b = b << 2;
Δ2    b = b leftOp 2; // result is b
```

6. LOR — Logical Operator Replacement:

Each occurrence of one of the logical operators (bitwise and - &, bitwise or - |, exclusive or - ^) is replaced by each of the other operators; in addition, each is replaced by leftOp and rightOp.

Examples:

```
      int a = 60;    int b = 13;
      int c = a & b;
Δ1    int c = a | b;
Δ2    int c = a rightOp b; // result is b
```

Mutation Operators for Java (5)

7. ASR — Assignment Operator Replacement:

Each occurrence of one of the assignment operators (=, +=, -=, *=, /=, %=, &=, |=, ^=, <<=, >>=, >>>=) is replaced by each of the other operators.

Examples:

```
      a = m * (o + p);
Δ1    a += m * (o + p);
Δ2    a *= m * (o + p);
```

8. UOI — Unary Operator Insertion:

Each unary operator (arithmetic +, arithmetic -, conditional !, logical ~) is inserted in front of each expression of the correct type.

Examples:

```
      a = m * (o + p);
Δ1    a = m * -(o + p);
Δ2    a = -(m * (o + p));
```

Mutation Operators for Java (6)

9. UOD — Unary Operator Deletion:

Each unary operator (arithmetic +, arithmetic -, conditional !, logical~) is deleted.

Examples:

```
      if !(X <= Y && !Z)
Δ1    if (X > Y && !Z)
Δ2    if !(X < Y && Z)
```

10. SVR — Scalar Variable Replacement:

Each variable reference is replaced by every other variable of the appropriate type that is declared in the current scope.

Examples:

```
      a = m * (o + p);
Δ 1   a = o * (o + p);
Δ 2   a = m * (m + p);
Δ 3   a = m * (o + o);
Δ 4   p = m * (o + p);
```

Mutation Operators for Java (7)

11. BSR — Bomb Statement Replacement:

Each statement is replaced by a special Bomb() function.

Example:

```
        a = m * (o + p);
Δ1   Bomb() // Raises exception when reached
```

Summary : Subsuming Other Criteria

- Mutation is widely considered the strongest test criterion
  - And most expensive !
  - By far the most test requirements (each mutant)
  - Usually the most tests
- Mutation subsumes other criteria by including specific mutation operators
- Subsumption can only be defined for weak mutation – other criteria only impose local requirements
  - Node coverage, Edge coverage, Clause coverage
  - General active clause coverage: Yes–Requirement on single tests
  - Correlated active clause coverage: No–Requirement on test *pairs*
  - All-defs data flow coverage